A Voltage Source Converter Model for Exchanging Active and Reactive Power with a Distribution Network

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Abstract. In this paper, some of the operational and design characteristics of a Distributed Superconducting Magnetic Energy Storage (D-SMES) device are presented. The main parts that a D-SMES consists of, the various configurations and operational techniques are discussed. The advantages and disadvantages of superconducting energy storage compared with other solutions are provided. The problems that a D-SMES can deal with are listed and discussed, but in the present work we will focus only on the ability of a D-SMES to alleviate voltage fluctuations and sags (dips) and support a sensitive load during power system outages or interruptions. To demonstrate this ability of a D-SMES device, simulations were performed using the ElectroMagnetic Transients for DC (EMTDC) simulation package. The simulation results are provided and discussed.

1. Introduction

Superconducting magnetic energy storage (SMES) is an energy storage technology that stores energy in the form of dc electricity that is the source of a dc magnetic field. The conductor for carrying the current operates at cryogenic temperatures where it is a superconductor and thus has virtually no resistive losses as it produces the magnetic field. The overall technology of cryogenics and superconductivity today is such that the components of a SMES device are defined and can be constructed. The integrated unit appears to be feasible for some utility applications at a cost that is competitive with other technologies. SMES is the only technology based on superconductivity that is applicable to the electric utilities and is commercially available today[1].

There are several other technologies for storing electric energy. Below, some of these alternative technologies including SMES are shortly described and the pros and cons of each one, are given:

- **DC storage capacitors**: They store energy in their capacitance and they need a dc/dc converter between the capacitance and the constant-voltage bus (Fig.1). They are suitable for short ridethrough times because their cost increases dramatically as the required ridethrough time increases.

- **Batteries**: They are the most commonly used method of storing energy. They are directly connected to the voltage-source converter (a dc/dc converter is not required). The limitations with batteries are not so much the amount of energy stored in it, but the speed with which this energy can be made available. Capacitors can compete with batteries but only for short ridethrough times. Their main disadvantages include their environmentally unfriendly materials, limited lifetime (in number of recharging cycles) and regular maintenance to ensure high reliability. However, there are newer types of batteries, which are being developed for use in electric vehicles, that do not have these disadvantages but they obviously have higher costs.

- **Supercapacitors**: Supercapacitors (or double-layer capacitors) are propagated as a future solution for energy storage to improve equipment voltage tolerance. They have energy densities comparable to batteries, but much longer lifetime and much less maintenance requirements. Their disadvantage is that they are only available for voltages of a few volts. For the supercapacitors currently in operation, the discharge time cannot be less than 1 minute. This makes them somewhat faster than batteries but still much slower than capacitors. The development of supercapacitors is mainly driven by the requirements of electric vehicles, where the amount of stored energy is of more importance than the speed with which it can be extracted.

- **Flywheels**: An alternative that is currently being investigated is the storage of energy in fast-spinning flywheels. They also require an additional dc/dc converter. Energy (kinetic) is stored in a rotating cylinder.

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This energy cannot be extracted completely, as the energy conversion becomes inefficient below a certain speed e.g. 50% of the maximum speed.

- **Superconducting coils**: They also require a dc/dc converter between the superconducting coil and the constant-voltage bus. They are the most cost-attractive solution for high-power short-time ride-through applications. For low-power short-time ride-through applications, capacitor storage is still the most cost-attractive solution. The amount of energy stored in an SMES is similar to the amount of energy stored in a battery but that energy can be made available much faster in an SMES. Some other benefits of superconducting coils are their quick and easy installation with short lead times, modular design to meet future load growth and portable in case it has to be moved to other locations [3].

## 2. Basic components of a D-SMES unit

A D-SMES unit is shown in Fig. 1 and consists of the following major items:

- **A voltage source converter (VSC)**. The VSC is designed to operate as either an inverter when discharging the superconducting coil or as a rectifier when charging. The VSC is designed with self-commutating static switches capable of supplying both active and reactive power needs of the system. Voltage and current ratings of the converter must be taken into account in the design of the control system. Moreover, the overload ratings must be known. For example, there are systems that can operate for 10 sec at about 200% of their steady-state ratings.

- **The superconducting magnetic energy storage system**. A superconducting (zero resistance) coil stores energy in its magnetic field. Some features of the storage system such as the charge and discharge time must be taken into account in the overall design of D-SMES.

- **A dc/dc converter (chopper)**. The chopper is used to maintain a constant dc voltage across the capacitor. The chopper frequency is defined by the manufacturer and results from an optimum tradeoff between the superconducting reactance, the dc capacitor and the maximum deviation for the dc voltage. Due to GTO losses the chopper frequency is generally between 500 Hz and 1 kHz [4].

- **A coupling (or step-up) transformer**. This transformer is used to raise the converter output voltage to meet network voltage level because of voltage limitations of converter’s power electronics. Another use is to provide electrical isolation from the grid. Typical value of transformer leakage reactance is about 0.1 pu. In some cases, simple reactors can be also used.

- **A harmonic filter**. The produced ac voltage waveform after the coupling transformer will contain some harmonics. This harmonic content may be low or high, which depends on the design of the voltage-source converter. In our case, a Pulse Width Modulated (PWM) converter is studied, whose harmonic content is significantly low for a quite high modulation frequency (e.g. 33). Thus, only a small capacitor can be used to meet harmonic requirements imposed by International Standards [5], [6]. Typical values are 0.3-0.6 pu of converter rating (MVA). In other cases, more complex filters may be used to mitigate the total harmonic content or some harmonics of specific order.

- **A system for data acquisition and control of the process**. Distribution network, load, converter and storage system parameters (e.g. voltages, currents, frequency, active and reactive power, load power factor) must be continuously measured to enable proper control of voltage-reactive power and frequency-active power.
(especially in isolated mode) and to protect from exceeding the device ratings and other design specifications.

Moreover, a Static Switch (SS) (or Solid-State Breaker SSB) may be used upstream the D-SMES system. The SS consists of a pair of anti-parallel self-commutating power electronic switches (e.g. GTO or IGBT). It takes a command to open when the system voltage drops below a pre-set rms value (or an interruption is detected). Thus, in case of faults on the distribution or the transmission system, the SS opens rapidly and the load is supplied from the energy storage reservoir through the voltage-source converter. Consequently, the voltage of the sensitive load is adequately supported. Without the SS, the D-SMES would require very large amounts of energy storage to adequately support the voltage of the sensitive load [2].

3. Description of D-SMES operational logic

The basic principle of a D-SMES is to use the VSC to generate a fast controllable ac voltage source $u = V \sin(wt - \psi)$ behind a leakage reactance. The voltage difference across the transformer reactance produces active and reactive power with the network. The exchange of reactive power with the network is obtained by controlling the magnitude $V$ and the exchange of active power results from a control of the phase shift $\psi$.

In other words, the D-SMES control system is designed to emulate a classical synchronous machine. There are two modes of operation for this device:

1. **On utility or Synchronized**, which defines the state where the controller is synchronized with the rest of the utility grid. D-SMES may be idle, charging, peak shaving, or just regulating voltage or var flow. Its controls must be coordinated with rest of the utility. Additional control signals may exist to maintain a scheduled power exchanged between the D-SMES and the distribution network.

2. **Islanded**, which defines the state when load is supplied only by the controller (the utility is disconnected). In this condition, the controller must be able to control not only voltage and reactive power but also frequency and active power.

For most operating conditions the D-SMES can be viewed as equivalent to a voltage source $V_B$ behind the transformer reactance $X_T$ as sketched in the equivalent circuit portion of Fig 2. The generated voltage $V_B$ is completely controllable within the current rating of the converter equipment. Consequently, the ac current can be supplied at any phase angle relative to the terminal voltage $V_T$, as shown in the phasor diagram. This feature permits the D-SMES to generate real and reactive power in all four quadrants as indicated by the circular capability curve. The D-SMES power generating capability is limited by the thermal rating of the converters and the available dc voltage. Overload capability will permit operation at higher currents for limited periods of time as suggested by the dotted capability curve.

![Fig. 2 Equivalent circuit of D-SMES](image)

The magnitude $V$ and the phase shift $\psi$ of the converter output voltage can be controlled using a proper switching pattern for the power electronics. In the present work, we consider the PWM pattern in which, magnitude and phase of the output voltage can be controlled by controlling the magnitude and the phase of the PWM carrier waveform [4].
4. Applications of a D-SMES unit

The capability of SMES systems to exchange active and reactive power with the electric network almost instantaneously, have made them suitable for enhancing power system dynamic performance [7]. A number of power system applications have been proposed over the past three decades. These applications include power system load leveling [8], power system stability improvement [9] [10], spinning reserve and damping of turbine-generator subsynchronous oscillations [11] [14], frequency and voltage control [13], protection from power outages and power and energy management [4].

The aforementioned applications imply connection of the device with the transmission system. However, a number of applications of the D-SMES system have been proposed for distribution networks. They include voltage stability improvement [3], protection of critical (sensitive) loads from power outages, reactive power compensation and mitigation of flicker and voltage sags. In case of distributed generation, D-SMES can be also used for load leveling and power and energy management.

5. Performance of a PWM-switched D-SMES

To demonstrate the performance of a D-SMES and a Static Switch, which is used for rapid disconnection of the sensitive load, EMTDC simulation package is used. The test system is shown in Fig. 3. A sensitive load is connected to a long distribution line. The D-SMES unit is connected at the load terminals (V_N) and the Static Switch is connected immediately before the D-SMES (Fig. 3). The D-SMES is responsible for maintaining the load voltage V_Ld within pre-set limits and the Static Switch is used to disconnect the load from the distribution line when these pre-set limits cannot be kept by the D-SMES e.g. in case of short-circuits on the distribution or the transmission system.

The load, power system and D-SMES parameters are given in Table 1. It must noted here that the dc side of the D-SMES system, that is the dc capacitor, the chopper and the superconducting coil are replaced by a dc voltage source in the simulations performed. This is done for simplicity, which does not alter significantly the performance characteristics of a D-SMES unit. Specifically, with this assumption the amount of energy stored (and available) is not taken into account and the response in the demand for active power is instantaneous. In a real D-SMES unit, this response would not be instantaneous but it would delay for only a few ms [16].

![Fig. 3 Test system](image)

<table>
<thead>
<tr>
<th>System and controller parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent source impedance Z_{src} (pu)</td>
<td>0.05</td>
</tr>
<tr>
<td>Transformer T_s leakage reactance (pu)</td>
<td>0.1</td>
</tr>
<tr>
<td>Distribution line length (km)</td>
<td>17</td>
</tr>
<tr>
<td>RL load MVA - Power Factor</td>
<td>10 – 0.9</td>
</tr>
<tr>
<td>Converter’s rating (MVA)</td>
<td>10</td>
</tr>
<tr>
<td>Filter (capacitor) MVA - \mu f</td>
<td>0.3 – 24</td>
</tr>
<tr>
<td>Transformer T_{conv} leakage reactance (pu)</td>
<td>0.1</td>
</tr>
<tr>
<td>DC voltage source (kV)</td>
<td>7.2</td>
</tr>
<tr>
<td>PWM modulation frequency</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 1 Load, power system and D-SMES parameters
As we mentioned in the beginning of this paper, the D-SMES will be studied for its ability to mitigate voltage fluctuations, sags and power outages (or interruptions). Thus, two cases are investigated, which are described in the following paragraphs.

5.1 Case 1

In this case, the performance of D-SMES to mitigate voltage fluctuations due to rapid load variations is demonstrated. D-SMES operates on utility or synchronized mode (Section 3). Load varies from 3 to 10 MVA (Fig. 4.1b) and it can be seen in Fig. 4.1a that the D-SMES response is almost instantaneous and the voltage fluctuations almost disappear. It was assumed that the D-SMES should inject only 1 MW of active power in such cases and in Fig. 4.1b the effort of the D-SMES to maintain this range is shown. The injected reactive power is also shown in Fig. 4.1b. The variation of D-SMES control parameters is shown in Fig. 4.1c.

In Fig. 4.2a, load voltage and current, and injected current waveforms are given. A high distortion in the injected current can be seen, which is verified by calculating the Total Harmonic Distortion (THD) factor (Fig. 4.2b). However, the load voltage and current are not so distorted and their THD factors are within the limits of international standards [5] [6]. Obviously, if lower harmonic distortion is required, a larger harmonic filter or higher modulation frequency (Table 1) could be used.

5.2 Case 2

The simulations for the second case are presented in Fig. 5.1 and 5.2. The D-SMES operates on the utility mode and injects a constant active power of 1 MW while the load apparent power is 7 MVA (Fig. 5.1b). At t=0.02 sec, a three-phase fault is applied on the distribution line (Fig. 5.1d). The distribution bus voltage $V_B$ (Fig. 3) dips (Fig. 5.2c) and when it reaches a value of 0.9 pu Static Switch receives a signal to disconnect the load from the distribution line. The Static Switch manages to disconnect the load within 300 µs and the load is now supplied by the D-SMES, which means that the D-SMES operates on the isolated mode (Section 3). The load voltage do not experience any serious voltage sag as it can be seen in Fig. 5.1a because in the beginning of the fault the voltage is supported by the D-SMES and the Static Switch operates very quickly. Some transients can be observed (Fig. 5.2a) on load phase voltages during the disconnection of load.
and change in operation mode, which do not create any serious problems. Moreover, the THD of load voltage and current during the operation in isolated mode are again low (Fig. 5.3). It should be noted here that in case of a voltage interruption, the Static Switch would operate in the same way and the performance of D-SMES would also be the same as shown in Fig. 5.1, 5.2 and 5.3.

Fig. 5.1 a) Load rms voltage with D-SMES and Modulation Amplitude factor  
b) Injected active and reactive power by the D-SMES and load apparent power  
c) Angle Order (phase shift)  
d) Fault occurs (transition from 0 to 1) at t=0.02 sec

Fig. 5.2 a) The three load phase voltages  
b) The three load line currents  
c) The three distribution bus phase voltages  
d) The three distribution bus line currents

Fig. 5.3 THD of load voltage and current

6. Conclusions

In this paper, a D-SMES unit is described and compared with devices that use other methods of energy storage. The benefits of such a device for a power system are thoroughly described. However, the present work focus on the ability of D-SMES to alleviate power quality problems such as voltage fluctuations, sags and interruptions. To demonstrate the behavior of D-SMES on such phenomena, simulations were performed.

The simulations verify that a D-SMES can efficiently mitigate voltage fluctuations caused by fast load variations with a small harmonic distortion of the load voltage. This harmonic distortion can be further eliminated by using a larger harmonic filter or higher modulation frequency. Moreover, it is shown that D-SMES can protect a sensitive load from faults on the distribution or the transmission system when it is accompanied with a Static Switch. Thus, the load experiences practically no voltage sag during the fault. The transition between the D-SMES two modes of operation is also investigated and the results show that not any serious transients appear. Finally, the harmonic distortion during the operation in isolated mode is within acceptable limits.
References